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Original Article

Development of low grade waste heat thermoelectric power generator

Suvit Punnachaiya*, Paiboon Kovitcharoenkul and Decho Thong-aram

Department of Nuclear Technology, Faculty of Engineering,
Chulalongkorn University, Patumwan, Bangkok, 10330 Thailand.

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Abstract

This research aimed to develop a 50 watt thermoelectric power generator using low grade waste heat as a heat source, in order to recover and utilize the excess heat in cooling systems of industrial processes and high activity radioisotope sources. Electricity generation was based on the reverse operation of a thermoelectric cooling (TEC) device. The TEC devices were modified and assembled into a set of thermal cell modules operating at a temperature less than 100°C. The developed power generator consisted of 4 modules, each generating 15 watts. Two cascade modules were connected in parallel. Each module comprised of 96 TEC devices, which were connected in series. The hot side of each module was mounted on an aluminum heat transfer pipe with dimensions 12.2×12.2×50 cm. Heat sinks were installed on the cold side with cooling fans to provide forced air cooling.

To test electricity generation in the experiment, water steam was used as a heat source instead of low grade waste heat. The open-circuit direct current (DC) of 250 V and the short-circuit current of 1.2 A was achieved with the following operating conditions: a hot side temperature of 96°C and a temperature difference between the hot and cold sides of 25°C. The DC power output was inverted to an AC power source of 220 V with 50 Hz frequency, which can continuously supply more than 50 watts of power to a resistive load as long as the heat source was applied to the system. The system achieved an electrical conversion efficiency of about 0.47 percent with the capital cost of 70 US$/W.

Keywords: thermoelectricity, Peltier cooler, waste heat, power generator, thermal cell, heat exchange

1. Introduction

The uncertainty in the availability and reliability of fossil-based fuels has resulted in developments of energy-saving and alternative sources. Utilization of fuels in industries and automotive engines results in more than 70% thermal energy being discharged into the environment as waste heat due to the Carnot limit of thermodynamics. If some of this waste heat could be recovered, a considerable amount of primary fuel could be saved. Therefore, the thermoelectric conversion technology becomes an interesting work in the energy conservation research. A 1 kW thermoelectric generator for heavy diesel truck was developed by Bass *et al.* (2001). Its hot side was placed on the diesel exhaust heat exchanger with an engine coolant to cool its cold side. The generator comprised of 72 HZ-14 thermoelectric generator (TEG) modules to convert engine heat exhaust directly into electricity. The modules were arranged 9 in one array and 8 parallel circuits at 12 volts DC during nominal engine operation. However, the TEG was manufactured for high grade waste heat recovery at temperatures of about 250-500°C. For low grade waste heat recovery, utilization of a reverse operation of a thermoelectric cooling (TEC) device for electricity generation is discussed in this research.

Related to this research, Kovitcharoenkul *et al.* (2007) developed a thermoelectric cell parametric test equipment for studying electrical and thermal characteristics of a thermoelectric cooler or a Peltier cooling device. A TEC1-12710

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* Corresponding author.
Email address: fnespn@eng.chula.ac.th

Peltier cooling device was tested and it was found that the performance could be modified to perform as the thermoelectric power generator, operating at a temperature range of 95-100°C. The DC voltage output at 250 V generated from the thermoelectric modules can be inverted into a city power of 220 volts AC 50 Hz for standard electrical appliances, using pulse width modulation (PWM) switching technology of power electronic system (Jhon *et al.*, 1992).

1.1 Basic Principles

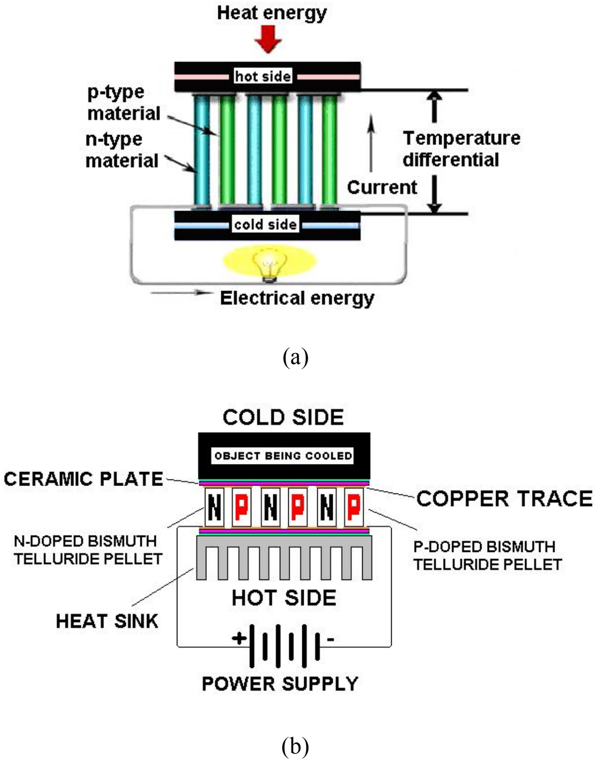
Seebeck (1821) and Peltier (1834) were first to discover the phenomena that are the basis for today's thermoelectric industry. Seebeck found that if a temperature gradient was placed across junctions of two dissimilar conductors, electrical current would flow. Peltier, on the other hand, learned that passing current through two dissimilar electrical conductors caused heat to be either emitted or absorbed at the junction of the materials. It was only after the mid 20th Century advancements in semiconductor technology that practical applications for thermoelectric devices became feasible. With modern techniques, thermoelectric "modules" that deliver efficient solid state heat pumping capability for both cooling and heating can be produced. Many of these units can also be used to generate DC power in special circumstances (e.g., conversion of waste heat). Electricity generation is based on the reverse operation of a thermoelectric cooling (TEC) device as shown in Figure 1 (Hendricks and Choate, 2006).

A thermoelectric converter consists of a number of alternate n- and p- type semiconductor thermo-elements, which are connected electrically in series by metal interconnects, sandwiched between two electrically insulating but thermally conducting ceramic plates to form a module. Provided that a temperature difference on the hot and cold sides is maintained across the module, electrical power will be delivered to an external load and the device will operate as a generator. Conversely, when an electric current is passed through the module, heat is absorbed at one face of the module and rejected at the other face; thus, the device operates as a refrigerator. Employing the effect, which Seebeck observed, thermoelectric power generators convert heat energy to electricity. When a temperature gradient is created across the thermoelectric device, a DC voltage develops across the terminals. When a load is properly connected, electrical current flows.

Inverters are always used to convert DC from a thermoelectric power generator to AC in order to run electrical equipment, motors, appliances, etc. The inverter is divided into two cascade stages. The first stage is a DC-to-DC converter which converts the 160-250 DC voltage at the inverter input to regulated 220 volts DC. The second stage is the actual inverter stage. It converts high voltage DC into 220 volts, 50 Hz AC. In the DC-to-DC converter stage, modern high frequency power switching conversion techniques are employed to eliminate bulky transformers, which are found in inverters based on older technology. The inverter stage uses advanced power MOSFET transistors in a full bridge configuration as shown in Figure 2.

1.2 Sources of Low Grade Waste Heat

According to the energy conversion efficiency, about 70% of consumed energy is dissipated untapped into the atmosphere. Therefore, an enormous amount of energy from many energy conversion processes is wasted. Much interest in energy saving is focused on technologies to recover and effectively utilize the waste energy. Thermoelectric conversion is a simple way to convert those waste heat sources into electricity. The waste heat at low temperature ranging from various sources has been investigated by the National Productivity Council of India under the Energy Efficiency in Thermal Utilities from Waste Heat Recovery Program as



(a)

(b)

Figure 1. Operating principle of thermoelectric devices, (a) Thermoelectric generator and (b) Thermoelectric cooler

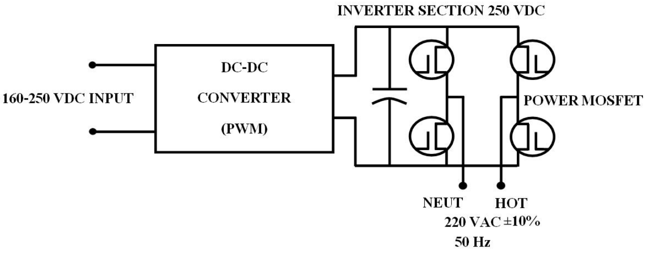


Figure 2. Principle operation of an inverter.

Table 1. Typical waste heat at low temperature range from various sources.

Source	Temperature,°C
Process steam condensate	55-88
Cooling water from: Furnace doors	32-55
Bearings	32-88
Welding machines	32-88
Injection molding machines	32-88
Annealing furnaces	66-230
Forming dies	27-88
Air compressors	27-50
Pumps	27-88
Internal combustion engines	66-120
Air conditioning and refrigeration condensers	32–43
Liquid still condensers	32-88
Drying, baking and curing ovens	93-230
Hot processed liquids	32-232
Hot processed solids	93-232

shown in Table 1. Most of the waste heat sources at a temperature range between 90-100°C are obtained from industrial cooling systems and are of interest for waste heat recovery by thermoelectric power generator.

2. Thermoelectric Power Generator Development

2.1 System design

From the thermoelectric power generation theory, the basic structure of the designed system is shown in Figure 3. The developed system consisted of a thermoelectric generator with a heat exchanging unit and an inverter. Peltier cooler devices were used as the thermal cell of the thermoelectric generator. During operation, waste heat energy was transferred to the hot side of the thermoelectric generator and the heat accumulated at the cold side was ventilated by a heat sink with cooling fan. The generated direct current (DC) power was inverted into an alternating current (AC) power of 50 W at 220 V, 50 Hz by an inverter.

2.2 Technical calculation

As shown in Figure 3, a 50 W inverter with high frequency power switching conversion techniques at input operation range of 160-250 VDC and efficiency of 83.33% was developed. This resulted in the required DC input for AC power conversion of 50 W/0.833 = 60 W. From the heat transfer experiment, the equilibrium temperature at the hot side (T_h) when a 100°C heat source was applied to the thermal cell under ventilation condition was 96 °C and cold side temperature (T_c) was 72°C. Therefore, the temperature difference was $T_h - T_c = 96\text{-}72 = 24$°C. The average temperature (T_{avg}) between the hot side and the cold side is given by

$$T_{avg} = \frac{T_h + T_c}{2} = \frac{96+72}{2} = 84°C = (84+273.2)K = 357.2K$$

Electrical and thermal characteristics of the TEC1-12710 Peltier cooler device were tested and used as the thermal cell. Tested results are shown in Table 2 and Figure 4. Technical parameters at ΔT = 24 K were obtained as follows: approximately 1 V open circuit voltage, 0.45 A short circuit current, 0.0507 V/K Seebeck coefficient, 1.48 K/W thermal resistance or 0.67568 W/K thermal conductance, and 2.5 Ω internal resistance.

All the above information was used to calculate the total number of thermal cells and the required heat source for generating 60-WDC power output. The following 8 major equations (Ferrotec, 2001-2008) were used:

Maximum output power from a cell is

$$P_{\max} = \frac{(S_M \times \Delta T)^2}{4 \times R_M} \tag{1}$$

Estimated number of cells needed is

$$N_T = \frac{P_o}{P_{\max}} \tag{2}$$

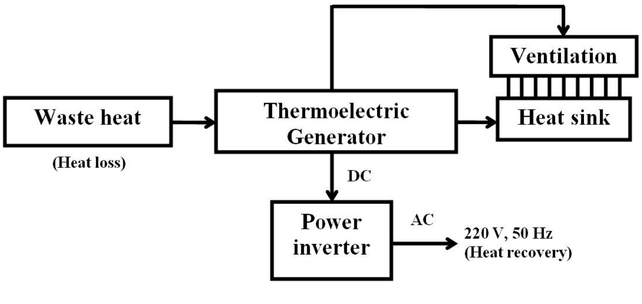


Figure 3. Block diagram of thermoelectric generator.

Table 2. Electrical parameter test of TEC1-12710 Peltier cooler device.

Temperature difference (K)	6	20	29
Internal resistance (Ω)	2.5	2.5	2.5
Open circuit voltage (V)	0.387	1.138	1.546
Short circuit current (A)	0.17	0.45	0.56

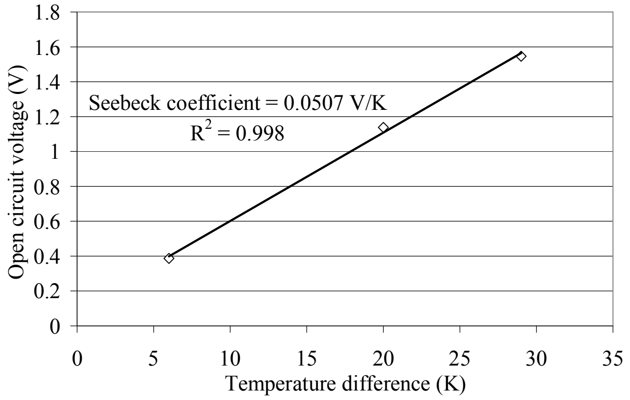


Figure 4. Temperature difference versus open circuit voltage, with the slope giving the Seebeck coefficient

The maximum power will be obtained when $R_M = R_L$ and when $V_O = V_{OC}/2$. It is desirable for most applications to select the series/parallel cell configuration that will best approximate this resistance balance of the module. At this condition, the load resistance at maximum power is given by

Load resistance

$$R_L = \frac{V_o^2}{P_o} \tag{3}$$

The output voltage at approximated load resistance is determined from Equation (3):

Output voltage is

$$V_o = \left[\frac{N_S \times S_M \times \Delta T}{\left(\frac{N_S \times R_M}{N_P} \right) + R_L} \right] \times R_L \tag{4}$$

The loaded output power and current of the module are given by

$$P_o = \frac{V_o^2}{R_L} \tag{5}$$

and $$I = \frac{P_o}{V_o} \tag{6}$$

The total heat input (Q_h) for DC power generation is

$$Q_h = N_T \left[\frac{S_M \times T_h \times I}{N_P} - 0.5 R_M \left(\frac{I}{N_P} \right)^2 + K_M \times \Delta T \right] \tag{7}$$

The generator efficiency (E_g) is

$$E_g = \frac{P_o}{Q_h} \times 100\% \tag{8}$$

In terms of thermal efficiency for electricity generation, if P_o is the electrical power (W_e) and if Q_h is the thermal power (W_{th}), equation (8) can be rewritten as

$$E_g = \frac{W_e}{W_{th}} \times 100\%, \tag{9}$$

where T_h = hot side temperature (K)
T_c = cold side temperature (K)
ΔT = temperature gradient across the cell (module) (K)
S_M = average Seebeck coefficient of cell (module) (V/K)
R_M = average internal resistance of cell (module) (Ω)
P_{max} = maximum power (W)
P_o = output power (W)
N_T = total number of thermal cell
N_S = number of thermal cells connected in series
N_P = number of thermal cells connected in parallel
V_O = loaded output voltage (V)
V_{OC} = open circuit voltage (V)
R_L = load resistance (Ω)
I = load current (A)
Q_h = total heat input (W)
K_M = thermal conductance (W/K)
E_g = generator efficiency (%)
W_{th} = thermal power (W) or (Btu/hr)
W_e = electrical power (W)

Results of the calculation obtained from Equation 1 to 9 for a thermoelectric power module structural design are found as follows: 0.148 W maximum power output of a cell, estimated number of cells needed for each module is 405 cells, 201.67 Ω internal load resistance of the module, 109.14 V module loaded voltage, 59.07 W_e output power, 0.545 A module loaded current, total heat input (W_{th}) required for DC power generation of 8,595.83 W_{th} and generator efficiency of

0.698 %. Additional information from the square pipe module heat transfer experiment indicated that the heat conduction efficiency is 80%. Therefore, the over all power generation efficiency (E_{gt}) can be found by

$$E_{gt} = 0.00698 \times 0.8 \times 0.8333 \times 100\,\% = 0.465\,\%$$

In the final design step, the total heat source required to generate 50 WAC electrical power is given by 50 WAC/ 0.00465 = 10,745.76 W or 36,675 Btu/hr.

2.3 Design and Construction

In designing the thermoelectric power generation system, both electrical and thermal characteristics of the module were determined. The size of the power module must be compact for the ease of installation and for obtaining a uniform temperature distribution on the hot side surface at low steam pressure. To maintain a temperature difference between a thermal load and the ambient environment, a certain amount of energy must be continually moved into (for heating) or out of (for cooling) the load. Therefore, heat sinks were installed on the cold side with cooling fans to provide forced air cooling.

From the technical structural design criteria, four power modules made of square pipe aluminum heat exchangers with 12.2×12.2×50 cm dimensions and 4 mm wall thickness were fabricated. Each module comprised of 96 thermal cells connected in series for generating 15 WDC at an open circuit voltage of 125 V and loaded voltage of 62.5 V. Twenty-four heat sinks with 4 cells each were fixed on the hot side surface of the power module. Four cooling fans with a set of ventilating fin channels for forced air cooling were arranged on the cold side. The steam heat source inlet and outlet were provided at both ends of the module as shown in the assembling diagram in Figure 5. The assembled power module with a total weight of 30 kg is shown in Figure 6. The total power of 60 WDC can be generated by connecting two modules in series and by connecting the 2-module sets in parallel, as illustrated in Figure 7.

2.4 System under test

2.4.1 Thermal characteristics

In this experiment, thermal characteristics such as uniformity of heat distribution and thermal response on the hot side surface of the power module's heat exchanger at 2 minutes sampling rate were studied. A 100°C steam generated by a 3500-watt boiling unit was fed through the power module under ventilated condition. Six sets of thermocouples were installed on the divided zone along the power module for hot surface temperature profile measurement. The test result of this experiment is shown in Figure 10.

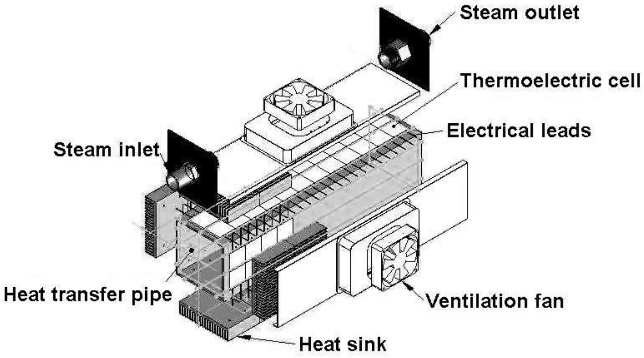


Figure 5. Designed structure of the power module.

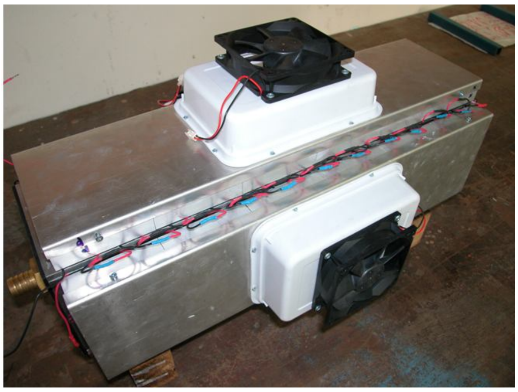


Figure 6. Assembled power module.

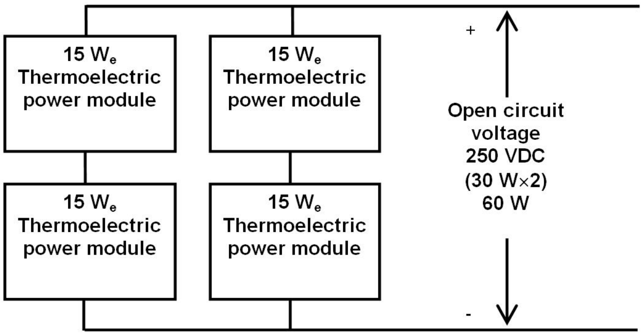


Figure 7. Connection diagram of the 60-WDC thermoelectric power generator.

2.4.2 Electrical characteristics

At thermal equilibrium, electrical characteristics of the developed power module such as open circuit voltage, short circuit current, and internal resistance were tested. The response of thermal energy conversion under different resistive loads was also tested by changing a set of resistive load from 25 Ω to 425 Ω. The relationship between voltage and current curve was obtained as shown in Figure 11.

2.4.3 Power generation

Power generation from the 50 watt thermoelectric power generator system was tested. The system consisted of a steam generator using a charcoal stove for boiling water, four power modules with configurations illustrated in the connection diagram in Figure 7, the inverter unit and two 25 W incandescent light bulbs connected in parallel acting as a power load. Various electrical test equipment pieces were used to monitor operating conditions. The set up of the system under test is shown in Figure 8. In this experiment, it took about 30 minutes of steam generation to obtain the steady temperature difference of about 25°C between hot side and cold side surfaces. A test of the system operation under full load is shown in Figure 9.

3. Results and Discussions

3.1 Results

There are two parts of the thermoelectric power generator test results: thermal and electrical characteristics.

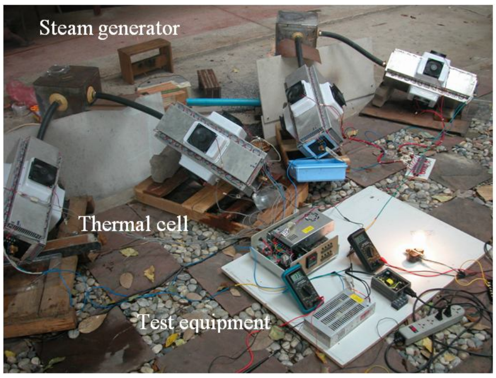


Figure 8. Test system and equipment set up.

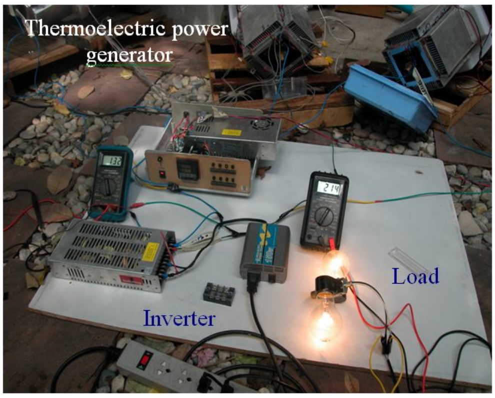


Figure 9. System under full load test.

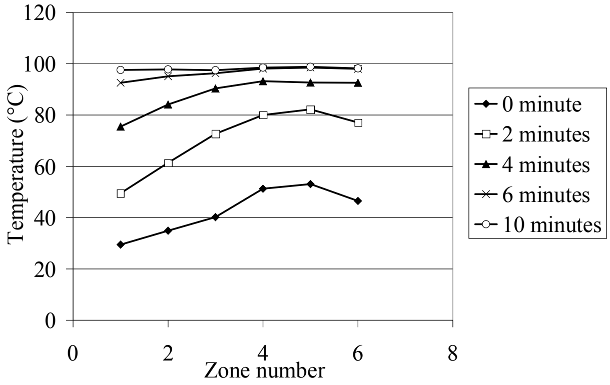


Figure 10. Power module thermal characteristics. Curves are shown for heat distribution and thermal response along the hot side zone.

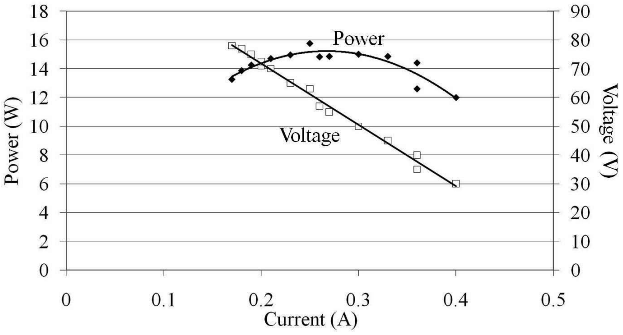


Figure 11. Power loading characteristics. Curves are illustrated the relationship between voltage and power of a power module.

Results in Figure 10 show the thermal characteristic obtained from heat distribution profiles on the hot side surface of the power module, recorded at 2-minute interval after steam was supplied. It was found that the hot side surface temperature at the outlet zone more rapidly increased. The power module took about 10 minutes to obtain a uniform temperature at the hot side along module of 98°C, while the temperature at the cold side was maintained at 73°C.

From electrical characteristic test results, the 126 V open circuit voltage and 0.64 A short circuit current with 250 Ω internal resistance were found. The relation of voltage versus current of power loading characteristic in Figure 11 showed that the maximum power loading of 15.22 W at 61.5 V loaded voltage and 0.25 A loaded current can be generated with a conversion efficiency of 0.45%.

A test of the system power generation at full load revealed the voltage and current at a load terminal of approximately 220 V_{rms} and 0.24 $A_{rms,}$ respectively. This indicates that the maximum load power of 52.8 WAC was achieved from the total thermal power source of approximately 10 kW and temperature difference of 25°C between hot side and cold side surfaces of the four power modules.

It was found that at full load tested, the DC input can be varied between 160-250 V.

3.2 Discussions

The electrical conversion efficiency of the thermoelectric power module is rather low (0.45%) compared to other alternative energy generators. However, it is a simple method for heat conversion with direct operation, and requires no storage battery. Besides, the system can continuously supply electrical power as long as the heat source is applied to the system. The outlet condensed water can also be recovered back to the boiling unit. From the experimental results, the developed power module's efficiency could be increased by reducing the heat sink temperature to 40°C by replacing the air cooling system with a water cooling system. To increase reliability and capability of electricity generation in continuous work, the heat exchange efficiency of pipe-type modules must be improved, as well as development of low cost fabrication technologies for heat exchangers to use with hot water rather than steam.

4. Conclusions

The Peltier cooling devices were applied as thermoelectric cells to develop a 50 W thermoelectric power generator for low grade waste heat recovery. The test results showed low efficiency of the developed system. In conditions where the cost of fuel is negligible or very low, the efficiency is not a major consideration. Capital investment and the lifetime of the conversion system are the dominant factors. Thermoelectric devices are inherently reliable, but are expensive. A capital cost of 70 US$/W was found and 76 % of the total cost was related to the TEC devices. In system operation, the output voltage can be regulated at less than ± 10% of power line standard by cooperation between heat source and power load regulations. The heat source of the boiler was manually controlled to maintain a temperature difference on the thermal cell, while load regulation was automatically controlled by pulse width modulation in power electronic technology to allow for operation in a wide range of input voltage supplied from the thermoelectric power module.

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